Researchers chart Orion Nebula like never before

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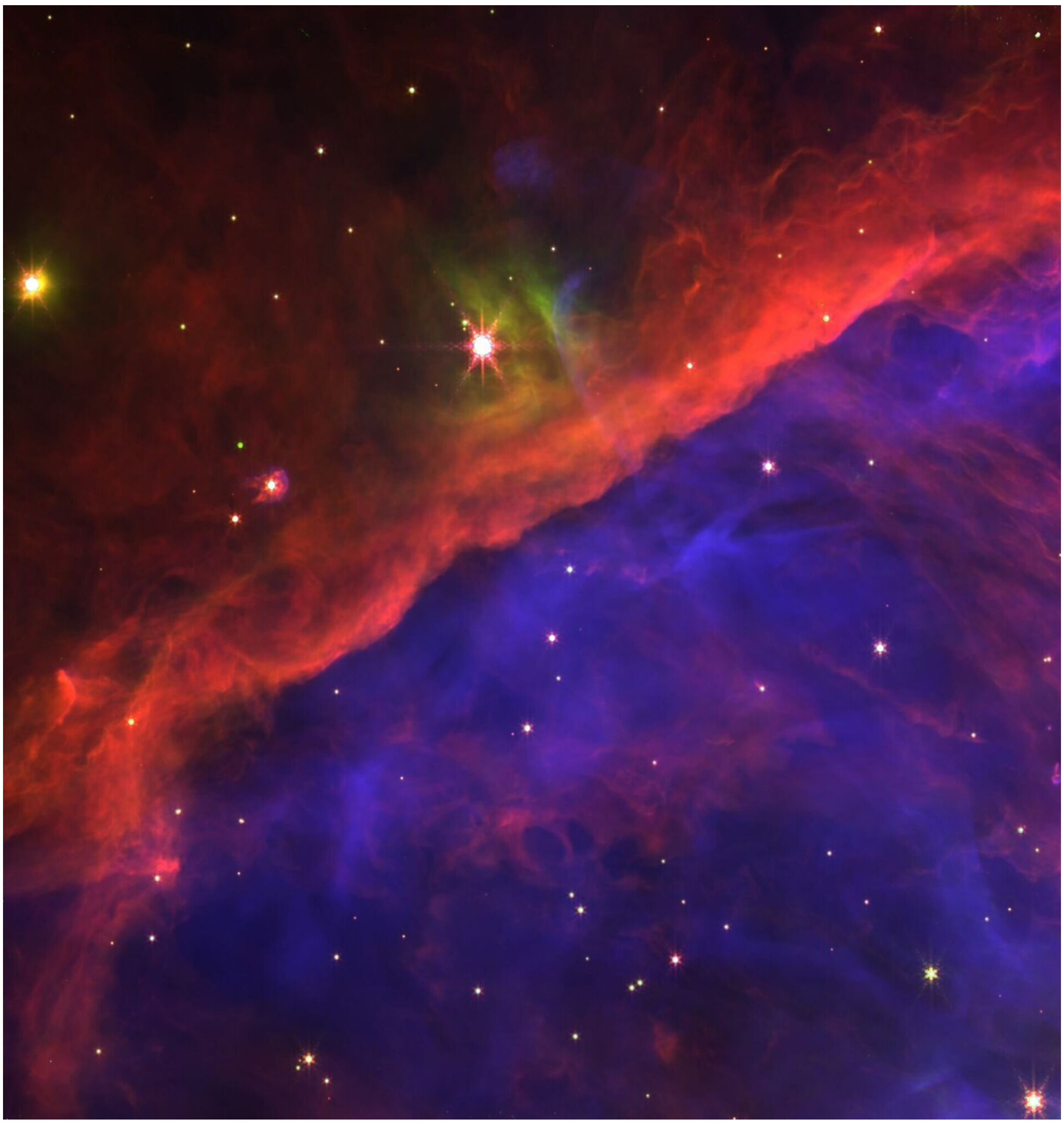

Looking near the heart of the Orion Nebula, this JWST image captures the Orion Bar. The Orion Bar is the fairly straight, diagonal feature that marks the transition from the hot ionized gas near the Trapezium stars to the cold molecular cloud on the other side of the bar. That material is the leftovers of the cloud from which these stars were formed. The stellar radiation of these young hot stars pounds on the Orion Bar transforming the gas and dust well beyond. The image is an RGB composite image with the blue colour showing emission from hot ionized gas (NIRCam filter F187N), the red colour showcasing emission from large carbonaceous molecules (NIRCam filter F335M), and the green colour tracing the warm dust and molecular gas (NIRCam filter F470N). North is up and East is left. Credit: NASA/ESA/CSA, E. Dartois, E. Habart, PDRs4All ERS team

Star and planet formation is a messy affair. It starts with the gravitational collapse of a gigantic cloud of gas and dust, which simultaneously produces massive stars, whose intense radiation field creates a harsh environment, as well as more modest stars, like our sun, surrounded by a planet-forming disk that is rich in organic materials.

Western University astrophysicists Els Peeters and Jan Cami and postdoctoral and graduate researchers Ryan Chown, Ameek Sidhu, Baria Khan, Sofia Pasquini, and Bethany Schefter were among the first scientists in the world to use the James Webb space telescope (Webb) for scientific research, and the focus was star formation.

"The process of star formation is messy because star-forming regions contain stars of varying masses at different stages of their development while still embedded in their natal cloud and because many different physical and chemical processes are at play that influence one another," said Peeters, a principal investigator of the PDRs4All JWST Early

Release Science program (ID1288) and faculty member as part of Western's Institute for Earth and Space Exploration.

Star formation is a very active field both in theoretical and observational astrophysics and Webb has turned out to be key in gaining insight into these processes.

"We do not yet fully understand how these processes sculpt or destroy planet-forming disks, nor when and how these disks are seeded with chemicals that are important for life. This is why we do what we do," said Cami, director of Western's Hume Cronyn Memorial Observatory and core member of PDRs4All.

Peeters co-leads the international PDRs4All consortium together with Emilie Habart from the University of Paris-Saclay, France and Olivier Berné from the University of Toulouse, France. The PDRs4All consortium consists of more than 120 researchers around the globe including astronomers, physicists and chemists whose complementary expertise allows them to fully leverage the gold mine of data obtained with Webb, the largest, most powerful telescope ever launched into space.

PDRs4All pointed Webb toward the Orion Bar, deep within the famous Orion Nebula, and collected a treasure trove of images and spectroscopic data. The main goal of the program is to unveil the detailed physical and chemical processes that are relevant for star- and planet-formation.

Along with their international collaborators, Peeters and Cami have now released a series of six papers in the journal *Astronomy & Astrophysics* that presents an overview of their work to date and the first deep dive into the nitty gritty details of what is going on in the Orion Bar.

Is this my best side?

Many of the key processes in interstellar space occur in so-called photo-dissociation regions (PDRs, hence the program name PDRs4All) where the physics and chemistry are fully determined by the interaction between UV radiation with gas and dust. The Orion Bar is the nearest PDR to Webb that offers its most useful and photogenic side to study these processes at small physical scales.

"The data are incredible and will serve as benchmarks for astrophysics research for decades to come," said Peeters. "So far, we have explored only a tiny fraction of the data, and this already resulted in several surprising and major discoveries."

In the past year, PDRs4All have released three major studies published in the journals *Nature*, *Nature Astronomy* and *Science*.

"I had the absolute pleasure to study the amazing Webb images in great detail," said Habart, who led the first new study published today (May 14) in *Astronomy & Astrophysics*. "The images are so incredibly beautiful and intricate; it's easy to see why so many people in the world were blown away when they first saw them."

With a mass 2,000 times greater than the sun, and visible to the naked eye, the Orion Nebula is the closest massive star-forming region and is therefore one of the most scrutinized and photographed objects in the Milky Way, and one of the public's favorite objects in the night sky.

The Webb images are unlike any other set, breathtaking in the incredible details they reveal, displaying all sorts of filaments and ridges of different shapes and colors, peppered with several small planet-forming disks.

Within the Orion Nebula lies the Orion Bar, a sharp, diagonal, ridge-like feature of gas and dust. The Orion Bar is essentially the edge of an astronomically large bubble carved out by some of the massive stars that power the nebula.

"The same structural details that give these images their aesthetic appeal reveals a more complicated structure than we originally thought—with foreground and background gas and dust making the analysis a bit harder.

"But these images are of such quality that we can separate these regions well and reveal that the edge of the Orion Bar is very steep, like a huge wall, as predicted by theories," said Habart.

Peeters, who was also a major player in the new series of *Astronomy & Astrophysics* studies, used near-IR spectroscopic data of the Orion Bar to bring the research to a whole new level.

"These images have such incredible detail that we will be scrutinizing them for many years to come," she said.

Spectroscopic observations split light up as a function of color and reveal many sharp peaks that are fingerprints of diverse chemical compounds in the collected infrared light.

A careful analysis of these fingerprints allows researchers to investigate the chemical makeup of the nebula, but there is much more: different combinations of these fingerprints can be used to measure the local temperature, density and strength of the radiation field, and by measuring these for each pixel, Peeters created maps of how these quantities change throughout the Orion Bar.

"The spectroscopic dataset covers a much smaller area of the sky compared to the images, but it contains a ton more information. A picture is worth a thousand words, but we astronomers only half-jokingly say that a spectrum is worth a thousand images," said Peeters, who measured no less than 600 spectroscopic fingerprints and used these to greatly improve existing PDR models.

The resulting data and improved PDR models were presented in the second study in *Astronomy & Astrophysics*, which Peeters led.

"What makes the Orion Bar truly unique is its edge-on geometry, giving us a ring-side seat to study in exquisite detail the different physical and chemical processes that happen as we move from the very exposed, harsh ionized region into the much more shielded regions where molecular gas can form," said Cami.

"This paper is a tour de force and took a real Herculean effort to complete, and it is a leap forward in our understanding of how changes in the physical environment affect chemistry and vice versa."

Leaving details in the dust

With the physical conditions all mapped out, the PDRs4All team turned its attention to another problem: that of dust emission. Previous observations had already revealed a steep variation in the dust emission in the Orion Bar, but the origin of these variations was not clear and presented a mystery that long stumped astrophysicists.

"The sharp hyper spectral Webb data contains so much more information than previous observations, that it clearly pointed to the attenuation of radiation by dust and the efficient destruction of the smallest dust particles as the underlying cause for these variations," said Institut d'Astrophysique Spatiale postdoctoral researcher Meriem Elyajouri.

Elyajouri modeled the dust emission across the illuminated edge of the

Orion Bar and led a third study describing the team's findings.

The remaining three papers, all deal with emission of large carbon-bearing molecules known as polycyclic aromatic hydrocarbons (PAHs), which represent one of the largest reservoirs of carbonaceous materials in the universe. PAHs contain up to 20% of all cosmic carbon, which makes them of relevance to our very own cosmic roots.

"We are studying what happens to carbonaceous molecules long before the carbon makes its way into our bodies," said Cami.

PAH emission is typically very bright and PAH molecules are incredibly sturdy and resilient.

"It is not surprising then that they turn out to be widespread across the universe and spread out such vast cosmological distances. Studying them in detail in nearby regions such as the Orion Bar where we have a good understanding of the local physical and chemical environment is therefore crucial to interpret observations of distant galaxies," said Sidhu, a former Western postdoctoral researcher.

Webb data shows the PAH emission bands in exquisite detail and reveal that the emission characteristics change due to radiation.

"It really is an embarrassment of riches," said Peeters. "Even though these large molecules are thought to be very sturdy, we found that UV radiation changes the overall properties of the molecules that cause the emission."

UV radiation in fact breaks up some of the smaller carbon molecules and changes how the bigger ones radiate.

"You actually see changes as you go from this very harsh environment to the more shielded environments," said former Western postdoctoral researcher Ryan Chown, who led the fourth study.

Machine learning multiplies

Chown's results are important new findings but were based on the analysis of only five small regions in the Orion Bar that are representative of the different environments throughout the Bar.

Sofia Pasquini, a master's student supervised by Peeters, used machine learning techniques to analyze the PAH emission in the entire data set consisting of many thousands of spectra. She too found that in regions with more UV radiation, PAHs are typically larger, likely because the smaller ones are destroyed. This is the basis of the fifth study.

"The machine learning techniques that Sofia used to interpret data mined from thousands of pixels produces essentially the same result that we found using the five representative regions using more traditional methods," said Peeters. "That gives us great confidence that our interpretation is more generally valid and thus a more powerful conclusion."

As it turns out, there are more than just changes in the sizes of the PAHs. Ilane Schroetter, a postdoctoral researcher of the University of Toulouse, France, also applied machine learning techniques to the data. His findings, published in the sixth study, confirm the effect of UV radiation on PAH size but also found very clear changes to the structure of the molecules too.

"These papers reveal some sort of survival of the fittest at the molecular level in the harshest environments in space," said Cami.

Webb is the most powerful space telescope in human history. Developed in partnership with NASA, the European Space Agency (ESA) and the Canadian Space Agency (CSA), it boasts an iconic 6.5-meter-wide mirror, consisting of a honeycomb-like pattern of 18 hexagonal, gold-coated mirror segments and a five-layer, diamond-shaped sunshield the size of a tennis court.

As a partner, CSA receives a guaranteed share of Webb's observation time, making Canadian scientists some of the first to study data collected by the most advanced space telescope ever built.

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tracer of physical properties of the interstellar medium in galaxies, *Astronomy & Astrophysics* (2024). DOI: 10.1051/0004-6361/202348974

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